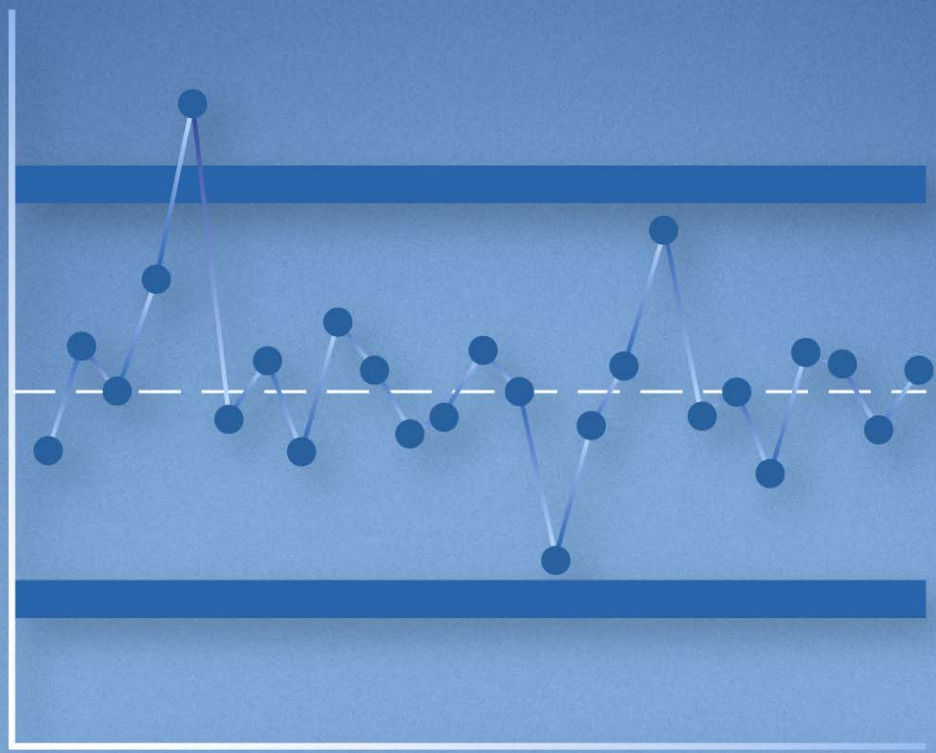


2020-04-06 - SOCOS



Quality Management in the Bosch Group | Technical Statistics

# 7. Statistical Process Control **SPC**



**BOSCH**  
Invented for life



**4<sup>th</sup> Edition, 07.2005**

3<sup>rd</sup> Edition dated 06.1994

2<sup>nd</sup> Edition dated 05.1990

1<sup>st</sup> Edition dated 09.1987

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## Introduction

Statistical Process Control (SPC) is a procedure for open or closed loop control of manufacturing processes, based on statistical methods.

Random samples of parts are taken from the manufacturing process according to process-specific sampling rules. Their characteristics are measured and entered in control charts. This can be done with computer support. Statistical indicators are calculated from the measurements and used to assess the current status of the process. If necessary, the process is corrected with suitable actions.

Statistical principles must be observed when taking random samples.

The control chart method was developed by Walter Andrew Shewhart (1891-1967) in the 1920's and described in detail in his book "Economic Control of Quality of Manufactured Product", published in 1931.

There are many publications and self-study programs on SPC. The procedures described in various publications sometimes differ significantly from RB procedures.

SPC is used at RB in a common manner in all divisions. The procedure is defined in QSP0402 [1] in agreement with all business divisions and can be presented to customers as the Bosch approach.

Current questions on use of SPC and related topics are discussed in the SPC work group. Results that are helpful for daily work and of general interest can be summarized and published as QA Information sheets.

SPC is an application of inductive statistics. Not all parts have been measured, as would be the case for 100% testing. A small set of data, the random sample measurements, is used to estimate parameters of the entire population.

In order to correctly interpret results, we have to know which mathematical model to use, where its limits are and to what extent it can be used for practical reasons, even if it differs from the real situation.

We differentiate between discrete (countable) and continuous (measurable) characteristics. Control charts can be used for both types of characteristics.

Statistical process control is based on the concept that many inputs can influence a process.

The "5 M's" – man, machine, material, milieu, method – are the primary groups of inputs. Each "M" can be subdivided, e.g. milieu in temperature, humidity, vibration, contamination, lighting, ....

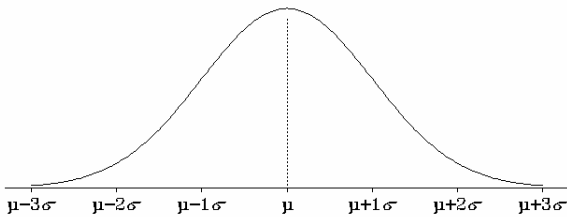
Despite careful process control, uncontrolled, random effects of several inputs cause deviation of actual characteristic values from their targets (usually the middle of the tolerance range).



The random effects of several inputs ideally result in a normal distribution for the characteristic.

Many situations can be well described with a normal distribution for SPC.

A normal distribution is characterized with two parameters, the mean  $\mu$  and the standard deviation  $\sigma$ .



The graph of the density function of a normal distribution is the typical bell curve, with inflection points at  $\mu - \sigma$  and  $\mu + \sigma$ .

In SPC, the parameters  $\mu$  and  $\sigma$  of the population are estimated based on random sample measurements and these estimates are used to assess the current status of the process.

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## 1. Terms for Statistical Process Control

### Process

A process is a series of activities and/or procedures that transform raw materials or pre-processed parts/components into an output product.

The definition from the standard [3] is: "Set of interrelated or interacting activities which transforms inputs into outputs."

This booklet only refers to manufacturing or assembly processes.

### Stable process

A stable process (process in a state of statistical control) is only subject to random influences (causes). Especially the location and variation of the process characteristic are stable over time (refer to [4])

### Capable process

A process is capable when it is able to completely fulfill the specified requirements. Refer to [11] for determining capability indices.

### Shewhart quality control chart

Quality control chart for monitoring a parameter of the probability distribution of a characteristic, in order to determine whether the parameter varies from a specified value.

### SPC

SPC is a standard method for visualizing and controlling (open or closed loop) processes, based on measurements of random samples. The goal of SPC is to ensure that the planned process output is achieved and that corresponding customer requirements are fulfilled.

**SPC is always linked to (manual or software supported) use of a quality control chart (QCC). QCC's are filled out with the goal of achieving, maintaining and improving stable and capable processes. This is done by recording process or product data, drawing conclusions from this data and reacting to undesirable data with appropriate actions.**



The following definitions are the same as or at least equivalent to those in [6].

**Limiting value**

Lower or upper limiting value

**Lower limiting value**

Lowest permissible value of a characteristic (lower specification limit *LSL*)

**Upper limiting value**

Highest permissible value of a characteristic (upper specification limit *USL*)

**Tolerance**

Upper limiting value minus lower limiting value:

$$T = USL - LSL$$

**Tolerance range**

Range of permissible characteristic values between the lower and upper limiting values

**Center point C of the tolerance range**

The average of the lower and upper limiting values:

$$C = \frac{USL + LSL}{2}$$

Note: For characteristics with one-sided limits (only *USL* is specified), such as roughness (Rz), form and position (e.g. roundness, perpendicularity), it is not appropriate to assume *LSL* = 0 and thus to set *C* = *USL* / 2 (also refer to the first comment in Section 4.1.1.1).

**Population**

The total of all units taken into consideration

**Random sample**

One or more units taken from the population or from a sub-population (part of a population)

**Random sample size n**

The number of units taken for the random sample

**Mean (arithmetic)**

The sum of the *x<sub>i</sub>* measurements divided by the number of measurements *n*:

$$\bar{x} = \frac{1}{n} \cdot \sum_{i=1}^n x_i$$

**Median of a sample**

For an odd number of samples put in order from the lowest to highest value, the value of the sample number (n+1)/2. For an even number of samples put in order from the lowest to highest value, normally the average of the two samples numbered n/2 and (n/2)+1. (also refer to [13])

Example: For a sample of 5 parts put in order from the lowest to the highest value, the median is the middle value of the 5 values.

**Variance of a sample**

The sum of the squared deviations of the measurements from their arithmetic mean, divided by the number of samples minus 1:

$$s^2 = \frac{1}{n-1} \cdot \sum_{i=1}^n (x_i - \bar{x})^2$$

**Standard deviation of a sample**

The square root of the variance:

$$s = \sqrt{s^2}$$

**Range**

The largest individual value minus the smallest individual value:

$$R = x_{max} - x_{min}$$



## 2. Planning

Planning according to the current edition of QSP 0402 “SPC”, which defines responsibilities.

SPC control of a characteristic is one possibility for quality assurance during manufacturing and test engineering.

### 2.1 Selection of Product Characteristics

Specification of SPC characteristics and their processes should be done as early as possible (e.g. by the simultaneous engineering team). They can also, for example, be an output of the FMEA.

Example of a simple procedure for inspection planning:

This should take

- Function,
- Reliability,
- Safety,
- Consequential costs of defects,
- The degree of difficulty of the process,
- Customer requests, and
- Customer connection interfaces, etc.

**Why do I need to know what, when, where and how exactly?**

**How large is the risk if I don't know this?**

Note: It may be necessary to add new SPC characteristics to a process already in operation. On the other hand, there can be reasons (e.g. change of a manufacturing method or introduction of 100% testing) for replacing existing SPC control with other actions.

into account.

SPC characteristics can be product or process characteristics.

The 7 W-questions can be helpful in specifying SPC characteristics (refer to “data collection” in “Elementary Quality Assurance Tools” [8]):

Why?	Who?
Which or what?	When?
Which number or how many?	With what or how exactly?
Where?	

#### 2.1.1 Test Variable

Definition of the “SPC characteristic”, direct or indirect test variable.

Note: If a characteristic cannot be measured directly, then a substitute characteristic must be found that has a known relationship to it.





## 2.1.2 Controllability

The process must be able to be influenced (controlled) with respect to the test variable. Normally manufacturing equipment can be directly controlled in a manner that changes the test variable in the desired way (small control loop).

According to Section 1, “control” in the broadest sense can also be a change of tooling, machine repair or a quality meeting with a supplier to discuss quality assurance activities (large control loop).

## 2.2 Measuring Equipment

Definition and procurement or check of the measuring equipment for the test variable.

Pay attention to:

- Capability of measuring and test processes,
- Objectiveness,
- Display system (digital),
- Handling.

The suitability of a measurement process for the tested characteristic must be proven with a capability study per [12].

In special cases, a measurement process with known uncertainty can be used (pay attention to [10] and [12]).

Note: The units and reference value must correspond to the variables selected for the measurement process.

## 2.3 Machinery

Before new or modified machinery is used, a machine capability study must be performed (refer to QSP0402 [1] and [11]). This also applies after major repairs.

Short-term studies (e.g. machine capability studies) register and evaluate characteristics of products that were manufactured in one continuous production run. Long-term studies use product measurements from a longer period of time, representative of mass production.

Note: The general definition of SPC (Section 1) does not presume capable machines. However, if the machines are not capable, then additional actions are necessary to ensure that the quality requirements for manufactured products are fulfilled.



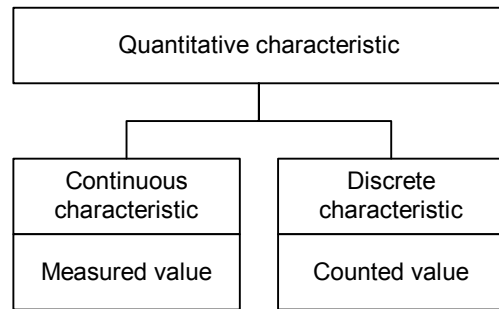
## 2.4 Types of Characteristics and Control Charts

This booklet only deals with continuous and discrete characteristics. Refer to [6] for these and other types of characteristics.

In measurement technology, physical variables are defined as continuous characteristics.

Counted characteristics are special discrete characteristics. The value of the characteristic is called a “counted value”. For example, the number of “bad” parts (defective parts) resulting from testing with a limit gage is a counted value. The value of the characteristic (e.g. the number 17, if 17 defective parts were found) is called a “counted value”.

SPC is performed with manually filled out form sheets (quality control charts) or on a computer. A control chart consists of a chart-like grid for entering numerical data from measured samples and a diagram to visualize the statistical indices for the process location and variation calculated from the data.



**If a characteristic can be measured, then a control chart for continuous characteristics must be used. Normally the  $\bar{x} - s$  chart with sample size  $n = 5$  is used.**

Control chart for continuous variables	
Control charts for process location	Control charts for process variation
$\bar{x}$ chart	$s$ chart
$(\tilde{x}$ chart)	$(R$ chart)
$x$ chart	



## 2.5 Random Sample Size

The appropriate random sample size is a compromise between process performance, desired accuracy of the selected control chart (type I and type II errors, operation characteristic) and the need for an acceptable amount of testing.

Normally  $n=5$  is selected. Smaller random samples should only be selected if absolutely necessary.

## 2.6 Defining the Interval for Taking Random Samples

When a control chart triggers action, i.e. when the control limits are exceeded, the root cause must be determined as described in Section 5.4, reaction to the disturbance initiated with suitable actions (refer to the action catalog) and a decision made on what to do with the parts produced since the last random sample was taken. In order to limit the financial “damage” caused by potentially necessary sorting or rework, the random sample interval – the time between taking two random samples – should not be too long.

The sampling interval must be individually determined for each process and must be modified if the process performance has permanently changed.

It is not possible to derive or justify the sampling interval from the percentage of defects. A defect level well below 1% cannot be detected on a practical basis with random samples. A 100% test would be necessary, but this is not the goal of SPC. SPC is used to detect process changes.

The following text lists a few examples of SPC criteria to be followed.

1. After setup, elimination of disturbances or after tooling changes or readjustment, measure continuously (100% or with random samples) until the process is correctly centered (the average of several measurements/medians!). The last measurements can be used as the first random sample for further process monitoring (and entered in the control chart).

2. Random sample intervals for ongoing process control can be defined in the following manner, selecting the shortest interval appropriate for the process.

Definition corresponding to the expected average frequency of disturbances (as determined in the trial run or as is known from previous process experience).

Approximately 10 random samples within this time period.

Definition depending on specified preventive tooling changes or readjustment intervals.

Approximately 3 random samples within this time period.

Specification of tooling changes or readjustment depending on SPC random samples.

Approximately 5 random samples within the average tooling life or readjustment interval.

But at least once for the production quantity that can still be contained (e.g. delivery lot, transfer to the next process, defined lots for connected production lines)!

3. Take a final random sample at the end of a series, before switching to a different product type, in order to confirm process capability until the end of the series.

Note: The test interval is defined based on quantities (or time periods) in a manner that detects process changes before defects are produced. More frequent testing is necessary for unstable processes.



### 3. Determining Statistical Process Parameters

#### 3.1 Trial Run

Definition of control limits requires knowledge or estimation of process parameters. This is determined with a trial run with sampling size and interval as specified in Sections 2.5 and 2.6. For an adequate number of parts for initial calculations, take a representative number of unsorted parts, at least  $m = 25$  samples (with  $n = 5$ , for example), yielding no fewer than 125 measured values.

It is important to assess the graphs of the measured values themselves, the means and the standard deviations. Their curves can often deliver information on process performance characteristics (e.g. trends, cyclical variations).

#### 3.2 Disturbances

If non-random influences (disturbances) occur frequently during the trial run, then the process is not stable (not in control). The causes of the disturbances must be determined and eliminated before process control is implemented (repeat the trial run).

#### 3.3 General Comments on Statistical Calculation Methods

Complicated mathematical procedures are no longer a problem due to currently available statistics software, and use of these programs is of course allowed and widespread (also refer to QSP0402 [1]).

The following procedures were originally developed for use with pocket calculators. They are typically included in statistics programs.

Note: Currently available software programs allow use of methods for preparing, using and evaluation control charts that are better adapted to process-specific circumstances (e.g. process models) than is possible with manual calculation methods. However, this unavoidably requires better knowledge of statistical methods and use of statistics software. Personnel and training requirements must take this into account.

Each business division and each plant should have a comprehensively trained SPC specialist as a contact person.



### 3.4 Process Average

Parameter  $\mu$  is estimated by:

$$\hat{\mu} = \bar{\bar{x}} = \frac{\sum_{j=1}^m \bar{x}_j}{m} = \frac{\text{total of the } \bar{x} \text{ values}}{\text{number of samples}}$$

or:

$$\hat{\mu} = \bar{\tilde{x}} = \frac{\sum_{j=1}^m \tilde{x}_j}{m} = \frac{\text{total of the medians}}{\text{number of samples}}$$

Example (Section 10):

$$\hat{\mu} = \bar{\bar{x}} = \frac{62.6 + 62.8 + \dots + 62.0}{25} = 62.3$$

$$\hat{\mu} = \bar{\tilde{x}} = \frac{63 + 63 + \dots + 62}{25} = 62.4$$

If  $\hat{\mu}$  significantly deviates from the center point C for a characteristic with two-sided limits, then this deviation should be corrected by adjusting the machine.



### 3.5 Process Variation

Parameter  $\sigma$  is estimated by:

$$\text{a) } \hat{\sigma} = \sqrt{\frac{1}{m} \cdot \sum_{j=1}^m s_j^2}$$

$$\hat{\sigma} = \sqrt{\frac{\text{total of the variances}}{\text{number of samples}}}$$

$$\text{or b) } \hat{\sigma} = \frac{\bar{s}}{a_n}, \text{ where}$$

$$\bar{s} = \frac{\sum_{j=1}^m s_j}{m} = \frac{\text{total of the standard deviations}}{\text{number of samples}}$$

$$\text{or c) } \hat{\sigma} = \frac{\bar{R}}{d_n}, \text{ with}$$

$$\bar{R} = \frac{\sum_{j=1}^m R_j}{m} = \frac{\text{total of the ranges}}{\text{number of samples}}$$

Example (Section 10):

$$\hat{\sigma} = \sqrt{\frac{0.55^2 + 0.45^2 + \dots + 2.55^2}{25}} = 1.41$$

Note:  $\hat{\sigma} = s$  is calculated directly from 25 **individual measurements** taken from sequential random samples (pocket calculator).

$$\bar{s} = \frac{0.55 + 0.45 + \dots + 2.55}{25} = 1.27$$

$$\hat{\sigma} = \frac{\bar{s}}{a_n} = \frac{1.27}{0.94} = 1.35$$

$n$	$a_n$
3	0.89
5	0.94
7	0.96

See Section 8, Table 1 for additional values

$$\bar{R} = \frac{1+1+\dots+6}{25} = 2.96$$

$$\hat{\sigma} = \frac{\bar{R}}{d_n} = \frac{2.96}{2.33} = 1.27$$

$n$	$d_n$
3	1.69
5	2.33
7	2.70

See Section 8, Table 1 for additional values

Note: The use of table values  $a_n$  and  $d_n$  presupposes a normal distribution!

Some of these calculation methods were originally developed to enable manual calculation using a pocket calculator. Formula a) is normally used in currently available statistics software.



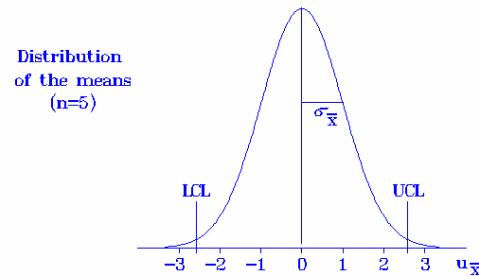
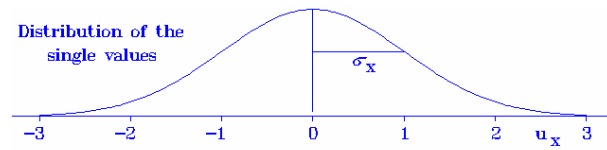
## 4. Calculation of Control Limits

### 4.1 Process-Related Control Limits

The control limits (lower control limit LCL and upper control limit UCL) are set such that 99% of all the values lie within the control limits in the case of a process which is only affected by random influences (random causes).

If the control limits are exceeded, it must therefore be assumed that systematic, non-random influences (non-random causes) are affecting the process.

These effects must be corrected or eliminated by taking suitable action (e.g. adjustment).



Relation between the variance (standard deviation  $\sigma_x$ ) of the single values (original values, individuals) and the variance (standard deviation  $\sigma_{\bar{x}}$ ) of the mean values:

$$\sigma_{\bar{x}} = \frac{\sigma_x}{\sqrt{n}}$$



### 4.1.1 Natural Control Limits for Stable Processes

#### 4.1.1.1 Control Limits for Location Control Charts (Shewhart Charts)

For two-sided tolerances, the limits for controlling the mean must always be based on the center point C.

Note: C is replaced by the process mean  $\hat{\mu} = \bar{\bar{x}}$  for processes where the center point C cannot be achieved or for characteristics with one-sided limits.

Example (Section 8):

Average Chart	$UCL = C + \frac{2.58}{\sqrt{n}} \cdot \hat{\sigma}$ $LCL = C - \frac{2.58}{\sqrt{n}} \cdot \hat{\sigma}$ <p>Also possible for normal distributions*:</p> $UCL = C + A^* \cdot \bar{s}$ $LCL = C - A^* \cdot \bar{s}$	$UCL = 62 + \frac{2.58}{\sqrt{5}} \cdot 1.35 = 63.6$ $LCL = 62 - \frac{2.58}{\sqrt{5}} \cdot 1.35 = 60.4$ $UCL = 62 + 1.23 \cdot 1.27 = 63.6$ $LCL = 62 - 1.23 \cdot 1.27 = 60.4$
Median Chart	$UCL = C + \frac{2.58}{\sqrt{n}} \cdot c_n \cdot \hat{\sigma}$ $LCL = C - \frac{2.58}{\sqrt{n}} \cdot c_n \cdot \hat{\sigma}$ <p>Also possible for normal distributions*:</p> $UCL = C + C_E \cdot \bar{R}$ $LCL = C - C_E \cdot \bar{R}$	$UCL = 62 + \frac{2.58}{\sqrt{5}} \cdot 1.2 \cdot 1.35 = 63.9$ $LCL = 62 - \frac{2.58}{\sqrt{5}} \cdot 1.2 \cdot 1.35 = 60.1$ $UCL = 62 + 0.59 \cdot 2.96 = 63.7$ $LCL = 62 - 0.59 \cdot 2.96 = 60.3$
Individual data Chart	$UCL = C + E'_E \cdot \hat{\sigma}$ $LCL = C - E'_E \cdot \hat{\sigma}$ <p>Also possible for normal distributions*:</p> $UCL = C + E_E \cdot \bar{R}$ $LCL = C - E_E \cdot \bar{R}$	$UCL = 62 + 3.09 \cdot 1.35 = 66.2$ $LCL = 62 - 3.09 \cdot 1.35 = 57.8$ $UCL = 62 + 1.33 \cdot 2.96 = 65.9$ $LCL = 62 - 1.33 \cdot 2.96 = 58.1$

\* Do not use for moving calculation of indices!

Note: Use of the median-R chart is only appropriate when charts are manually filled out, without computer support.

$n$	$A^*$	$C_E$	$c_n$	$E'_E$	$E_E$
3	1.68	1.02	1.16	2.93	1.73
5	1.23	0.59	1.20	3.09	1.33
7	1.02	0.44	1.21	3.19	1.18

Estimated values  $\hat{\mu}$  and  $\hat{\sigma}$  are calculated per Sections 3.4 and 3.5.

Refer to Section 8 Table 2 for additional values.





Comments on the individual data chart:  
Use an  $\bar{x} - s$  chart to perform the capability study (trial run). Estimate  $\hat{\mu}$  and  $\hat{\sigma}$  for the mean  $\mu$  and the standard deviation  $\sigma$  of the population from at least  $m = 25$  random samples (with, for example,  $n = 5$ ), for a minimum of 125 measurements.

These formulas are based on the assumption of normally distributed individual values. Deviations from the normal distribution can cause larger nonconforming fractions.

Fill out the chart by periodically taking random samples of size  $n$  (e.g.  $n = 5$ ), numerically entering the data in the chart (if possible) and displaying the individual data in the chart graph.

To evaluate the chart (e.g. ongoing calculation of  $C_p$  and  $C_{pk}$  indices), it is necessary to calculate  $\bar{x}$  and  $s$  or  $\tilde{x}$  and  $R$  from the random sample data ( $n$  measurements) for the full control chart and to continue as with an  $\bar{x} - s$  chart according to [11].

Comments on the average chart:  
For characteristics with one-sided limits (or in general for skewed distributions) and small  $n$ , the random sample averages are not necessarily normally distributed. It could be appropriate to use a Pearson chart in this case.

This chart has the advantage compared to the Shewhart chart that the control limits are somewhat wider apart. However, it has the disadvantage that calculation of the control limits is more complicated, in actual practice only possible on the computer.

### Control charts with moving averages

The  $\bar{x}$  chart with a moving average is a special case of the  $\bar{x}$  chart. For this chart, only single random samples are taken.

$n$  sample measurements are formally grouped as a random sample and the average of these  $n$  measurements is calculated as the mean.

For each new measurement from a single random sample that is added to the group, the first measurement of the last group is deleted, yielding a new group of size  $n$ , for which the new average is calculated.

Example for  $n = 1(3)$ :

<u>3</u> <u>7</u> <u>4</u>	$\bar{x}_1 = 4.7$
3 <u>7</u> <u>4</u> <u>9</u>	$\bar{x}_2 = 6.7$
3 7 <u>4</u> <u>9</u> <u>2</u>	$\bar{x}_3 = 5.0$
3 7 4 <u>9</u> <u>2</u> <u>8</u>	$\bar{x}_4 = 6.3$

Of course, moving averages calculated in this manner are not mutually independent. That is why this chart has a delayed reaction to sudden process changes. The control limits correspond to those for "normal" average charts:

$$LCL = C - \frac{2.58}{\sqrt{n}} \cdot \hat{\sigma} \quad UCL = C + \frac{2.58}{\sqrt{n}} \cdot \hat{\sigma}$$

Calculate  $\hat{\sigma}$  according to Section 3.5 a)

Control limits for  $n = 1(3)$ :

$$LCL = C - 1.5 \cdot \hat{\sigma} \quad UCL = C + 1.5 \cdot \hat{\sigma}$$

This approach for moving sample measurements can also be applied to the variation, so that an  $\bar{x} - s$  chart with a moving average and moving standard deviation can be used.

After intervention in the process or process changes, previously obtained measurements may no longer be used to calculate moving indices.



### 4.1.1.2 Control Limits for Variation Control Charts

The control limits to monitor the variation (depending on  $n$ ) relate to  $\hat{\sigma}$  and  $\bar{s}$  and likewise  $\bar{R}$  (= "Central line").

$s$  chart

a) generally applicable formula  
(also for the moving  $\bar{x} - s$  chart)

$$UCL = B'_{Eob} \cdot \hat{\sigma}$$

$$LCL = B'_{Eun} \cdot \hat{\sigma}$$

Example (Section 10):

$$UCL = 1.93 \cdot 1.35 = 2.6$$

$$LCL = 0.23 \cdot 1.35 = 0.3$$

b) for standard  $\bar{x} - s$  chart

$$UCL = B^*_{Eob} \cdot \bar{s}$$

$$LCL = B^*_{Eun} \cdot \bar{s}$$

Note: Formula a) must be used in the case of moving  $s$  calculation. Calculation of  $\hat{\sigma}$  per Section 3.5 a).

$$UCL = 2.05 \cdot 1.27 = 2.6$$

$$LCL = 0.24 \cdot 1.27 = 0.3$$

$R$  chart

$$UCL = D_{Eob} \cdot \bar{R}$$

$$LCL = D_{Eun} \cdot \bar{R}$$

$$UCL = 2.1 \cdot 2.96 = 6.2$$

$$LCL = 0.24 \cdot 2.96 = 0.7$$

Table

$n$	$B'_{Eun}$	$B'_{Eob}$	$B^*_{Eun}$	$B^*_{Eob}$	$D_{Eun}$	$D_{Eob}$
3	0.07	2.30	0.08	2.60	0.08	2.61
5	0.23	1.93	0.24	2.05	0.24	2.10
7	0.34	1.76	0.35	1.88	0.34	1.91

See Section 8, Table 2 for further values



## 4.1.2 Calculating Control Limits for Processes with Systematic Changes in the Average

If changes of the mean need to be considered as a process-specific feature (trend, lot steps, etc.) and it is not economical to prevent such changes of the mean, then it is necessary to extend the “natural control limits”.

The procedure for calculating an average chart with extended control limits is shown below.

The overall variation consists of both the “inner” variation (refer to Section 3.5) of the random samples and of the “outer” variation between the random samples.

### Calculation procedure

### Control limits for the mean

#### Standard deviation of the means

$$\hat{\sigma}_{\bar{x}} = s_{\bar{x}} = \sqrt{\frac{1}{m-1} \cdot \sum_{j=1}^m (\bar{x}_j - \bar{\bar{x}})^2}$$

Calculate  $\hat{\mu}$  according to Section 3.3

$$UCL = C + 2.58 \cdot \hat{\sigma}_{\bar{x}}$$

$$LCL = C - 2.58 \cdot \hat{\sigma}_{\bar{x}} \quad C = \text{center point}$$

Note: For processes that cannot be controlled about the mean, replace  $C$  with the process mean  $\hat{\mu}$ .

#### Determining outer variation with analysis of variance (ANOVA)

The variation between random samples  $\hat{\sigma}_{add}$  can be determined with analysis of variance using suitable software (ANOVA model II).

$$UCL = \hat{\mu} + 2.58 \cdot \frac{\hat{\sigma}}{\sqrt{n}} + 1.5 \cdot \hat{\sigma}_{add}$$

$$LCL = \hat{\mu} - 2.58 \cdot \frac{\hat{\sigma}}{\sqrt{n}} - 1.5 \cdot \hat{\sigma}_{add}$$

Calculate the **inner variation** (standard deviation)  $\hat{\sigma}$  according to Section 3.5

#### Total standard deviation

(standard deviation of all individual measurements)

$$\hat{\sigma} = s_{total} = \sqrt{\frac{1}{N-1} \cdot \sum_{i=1}^N (x_i - \bar{\bar{x}})^2} \quad N = n \cdot m$$

Calculate  $\hat{\mu}$  according to Section 3.3

$$UCL = \hat{\mu} + 2.58 \cdot \frac{\hat{\sigma}}{\sqrt{n}}$$

$$LCL = \hat{\mu} - 2.58 \cdot \frac{\hat{\sigma}}{\sqrt{n}}$$

#### Estimating the upper and lower process location limits

$\hat{\mu}_{max}$  = Average of the 3 largest averages  $\bar{x}_i$

$\hat{\mu}_{min}$  = Average of the 3 smallest averages  $\bar{x}_i$

Calculate  $\hat{\sigma}$  according to Section 3.5

$$UCL = \hat{\mu}_{max} + 2.58 \cdot \frac{\hat{\sigma}}{\sqrt{n}}$$

$$LCL = \hat{\mu}_{min} - 2.58 \cdot \frac{\hat{\sigma}}{\sqrt{n}}$$



## 4.2 Acceptance Control Chart (Tolerance-Related Control Limits)

For processes with system-related average changes, the control limits can be based on tolerances in special cases (e.g. mechanical processing with stepped bores, internal turning tools, form disk). A prerequisite for this is that the inner variation is small enough compared to the tolerance ( $\hat{\sigma}$  per Section 3.5),

$$\text{i.e. } \frac{T}{\hat{\sigma}} \geq 10.$$

When tolerance-related control limits are used, the process is always controlled worse than when natural control limits are used, since they focus on staying within the tolerance and not on improving the process (stabilization, centering).

Tolerance-related  $\bar{x}$  or  $\bar{x}$  charts are calculated using the following formulas:

$$UCL = USL - k_A \cdot \hat{\sigma}$$

$$LCL = LSL + k_A \cdot \hat{\sigma}.$$

$k_A$  is called the delimitation factor (refer to Section 3.5 for calculating  $\hat{\sigma}$ ).

Control limits for corresponding  $s$  or  $R$  charts are calculated according to Section 4.2.2.

### Specifying the delimitation factor

The delimitation factor is specified so that a nonconforming fraction of  $p = 1\%$  is indicated with  $P_A = 99\%$  probability.

In the following formulas,  $u_{1-p}$  and  $u_{P_A}$  are the percentage points (quantiles) of the normal distribution of the probabilities  $1-p$  or  $P_A$  or  $\sqrt[n]{1-P_A}$ .

$$\text{Average chart: } k_A = u_{1-p} + \frac{u_{P_A}}{\sqrt{n}}$$

$p = 1\%$  and  $P_A = 99\%$  yield:

$n$	$k_A$
3	3.7
4	3.5
5	3.4
6	3.3

$$\text{Individual data chart: } k_E = u_{1-p} - u_{\sqrt[n]{1-P_A}}$$

$p = 1\%$  and  $P_A = 99\%$  yield:

$n$	$k_E$
3	3.1
4	2.8
5	2.6
6	2.4

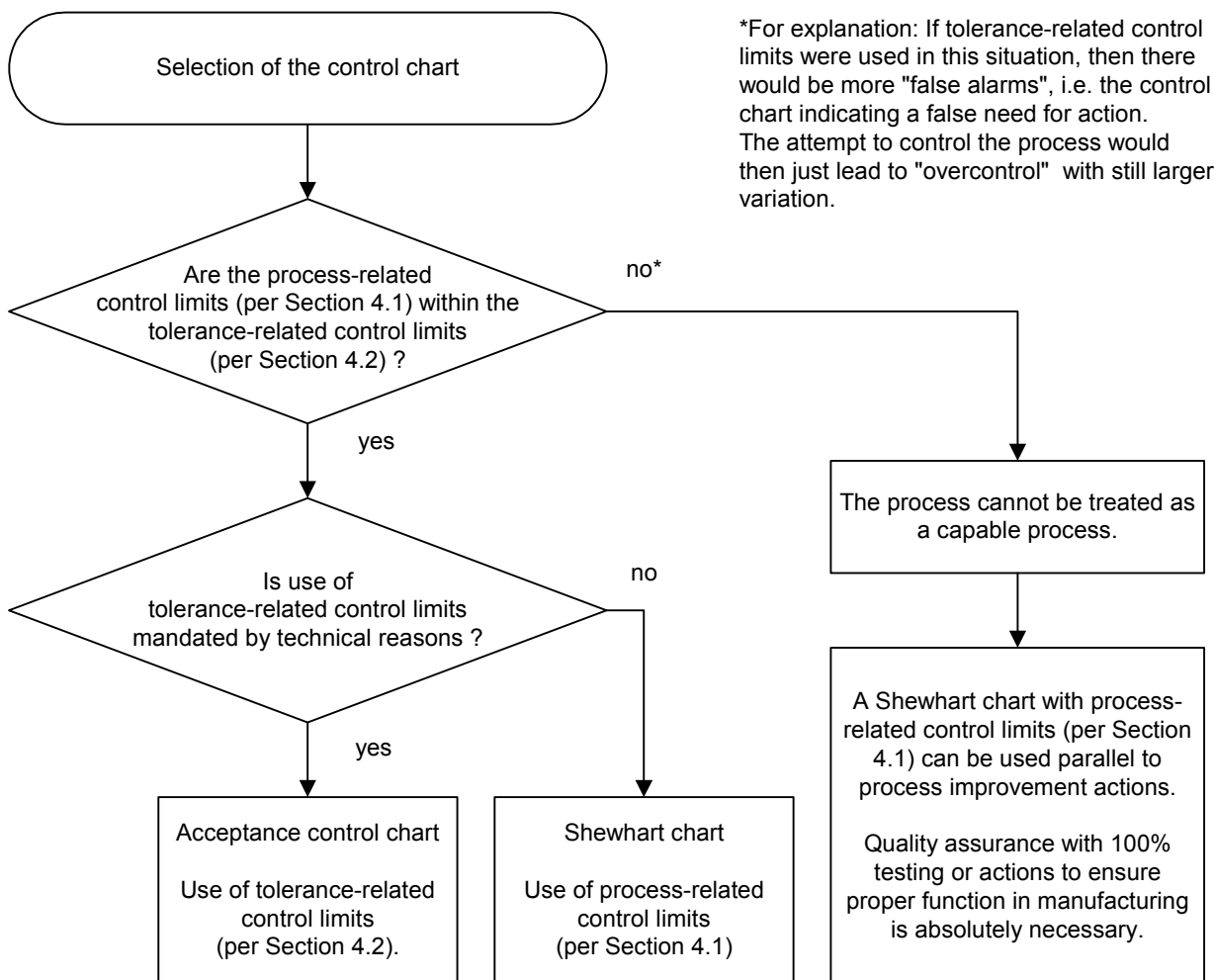


### 4.3 Selection of the Control Chart

Independent of the type of process, the process-related and also the tolerance-related control limits should be calculated. Knowledge and comparison of both types of control limits is important for correct selection of the type of chart (refer to the explanation).

**When tolerance-related control limits are used, the process is always controlled worse than when natural (process-related) control limits are used, since they focus on staying within the tolerance and not on improving the process (stabilization, centering).**

Selection of the control chart is performed with the flow chart below.



When using the Shewhart chart, tolerance-related control limits can be used to assist in decision making during sorting actions (refer to Section 9.4). These limits are then referred to as alarm limits.

It is not permissible to draw tolerance-related control limits (alarm limits) as lines in Shewhart control charts.



#### 4.4 Characteristics of the Different Types of Control Charts

	Characteristics
Individual data Chart	<ul style="list-style-type: none"> <li>• Presentation of all individual data from the random sample, so the chart is especially easy to understand and to fill out, lending it suitable for simple documentation of the manufacturing process.</li> <li>• No calculation is necessary to use the chart.</li> <li>• The individual data chart reacts to both a shift of the average location as well as to an increase of the standard deviation of a characteristic.</li> <li>• Compared to the <math>\bar{x} - s</math> chart and the <math>\tilde{x} - R</math> chart less sensitivity or selectivity with respect to a shift of the average location as well as to an increase of the standard deviation <math>\sigma</math>.</li> <li>• A decrease of <math>\sigma</math> is not indicated by going below a limit value.</li> <li>• More sensitivity to deviations of the population from a normal distribution than with the average chart.</li> <li>• Potential confusion of users from the fact that, for example, the <math>UCL</math> increases with larger sample sizes <math>n</math>.</li> <li>• Evaluation, such as calculation of <math>Cpk</math>, is more complicated, because the original data is usually not recorded numerically (e.g. only points on the graph).</li> </ul>
Average Chart	<ul style="list-style-type: none"> <li>• For the same sample size, better sensitivity or selectivity than the <math>\tilde{x} - R</math> and the individual data charts with respect to a shift of the average location as well as to an increase of the standard deviation <math>\sigma</math>.</li> <li>• For <math>n \geq 4</math> insensitive to deviation of the population from the normal distribution</li> <li>• Preferred chart for use with computers</li> </ul>
Chart for Moving Indices	<ul style="list-style-type: none"> <li>• Can also be used for destructive or complicated testing</li> <li>• This chart has a delayed reaction to suddenly occurring process changes.</li> <li>• The control limits are the same as for “normal” average charts</li> </ul>
Average Chart with Extended Limits	<ul style="list-style-type: none"> <li>• Preferred chart for processes with systematic changes of the average</li> </ul>
Acceptance Control Chart	<ul style="list-style-type: none"> <li>• Due to the tolerance-related control limits, the process is controlled worse than with process-related control limits.</li> </ul>



## 5. Preparation and Use of Control Charts

### 5.1 Reaction Plan (Action Catalog)

Reaction plans are created for when control limits are exceeded and for dealing with unusual data sequences. This plan must be specifically made for the process, machine or machine type. It should list all actions

- For finding the causes of disturbances, and
- That are needed for controlling the process.

The plan should also include clear instructions on what to do with the parts manufactured since the last random sample.

Note: If helpful, define codes.

### 5.2 Preparation of the Control Chart

All known data is entered in the control chart, including:

- Nominal value
- Lower and upper specification limits (tolerance limits)
- Center point  $C$  (“middle of the tolerance”),
- Reference value and its units
- Control limits.

Enter the scale for the  $\bar{x}$  (or  $\tilde{x}$ ) and  $s$  (or  $R$ ) diagram.

Draw the average and the control limit lines.

**It is not permissible to draw lines for LSL and USL (tolerance limits) in a control chart (also refer to Section 5.5).**

### 5.3 Use of the Control Chart

Define who will fill out the chart and who will perform control actions.

The individual measurements must be entered.

$\bar{x}$  (or  $\tilde{x}$ ) and  $s$  (or  $R$ ) must be calculated and entered.

$\bar{x}$  (or  $\tilde{x}$ ) and  $s$  (or  $R$ ) points are drawn in the diagram and the series of points is connected with lines.

If an entry is outside of the control limits, then control actions per the action plan (Section 9) must be initiated.

The completed actions are noted on the chart at the point where the control limit was exceeded (or a note is made to refer to the reverse side of the chart).

Note:

In order to be able to sort out bad parts after a control limit was exceeded, it is essential to be able to trace the production quantity manufactured since the last random sample was taken.



## 5.4 Evaluation and Control Criteria

After each entry, check whether one of the two chart traces indicates a reason for intervention, i.e. whether a control criteria is fulfilled.

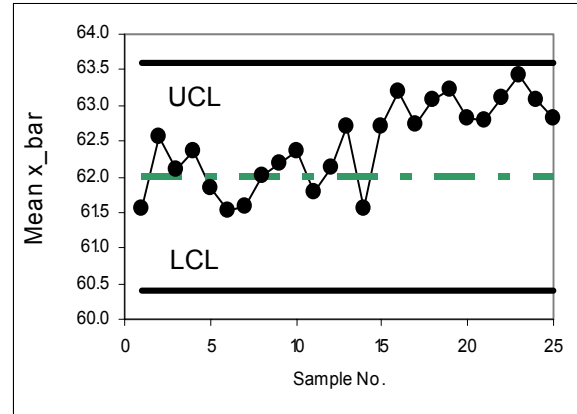
Intervention means, in general, adequate reaction to an event that is unusual in a statistical sense (one of the control criteria is fulfilled). This means that we have to check whether the process behavior has actually changed, and if this is confirmed, the original process behavior has to be re-established with suitable actions after the causes have been determined. Then we have to decide on what to do with the parts manufactured since the last random sample, e.g. with a sorting instruction. This means that we must always be able to still access these parts if there is a quality risk.

In order to ensure a simple and effective procedure, a process-specific reaction plan for causes, actions and dealing with parts is created when the control chart is being prepared. When control is necessary, the appropriate random sample statistic is marked on the control chart and the causes, actions and disposition of parts are documented (refer to Section 9) on the back of the chart (if appropriate, in coded form).

Control criteria:

- The control chart indicates the need for action, i.e. at least one random sample statistic is outside of the control limits.
- Individual data are out of tolerance (at least one), in which case the control chart does not necessarily indicate the need for action.
- There is an unusual sequence of points, i.e. at least 7 points in a row on one side of the average line, or forming a continuously increasing or decreasing trend (rule of 7, refer to the following figure).

Note: The rule of 7, in the simplest case (7 points on one side of the average line), is based on the assumed random process behavior and the at least approximately normal distribution of the random sample statistics. Of course, it cannot be used for processes with systematic changes of the average.



Since for average charts and stable process behavior, each point has a 50% probability of being above or below the average line, independent of the previous point, the probability of seven points in a row being on one side of the average line is

$$(0.5)^7 = 0.008 < 1 \%$$

This is why it is called an “unusual sequence of points”.

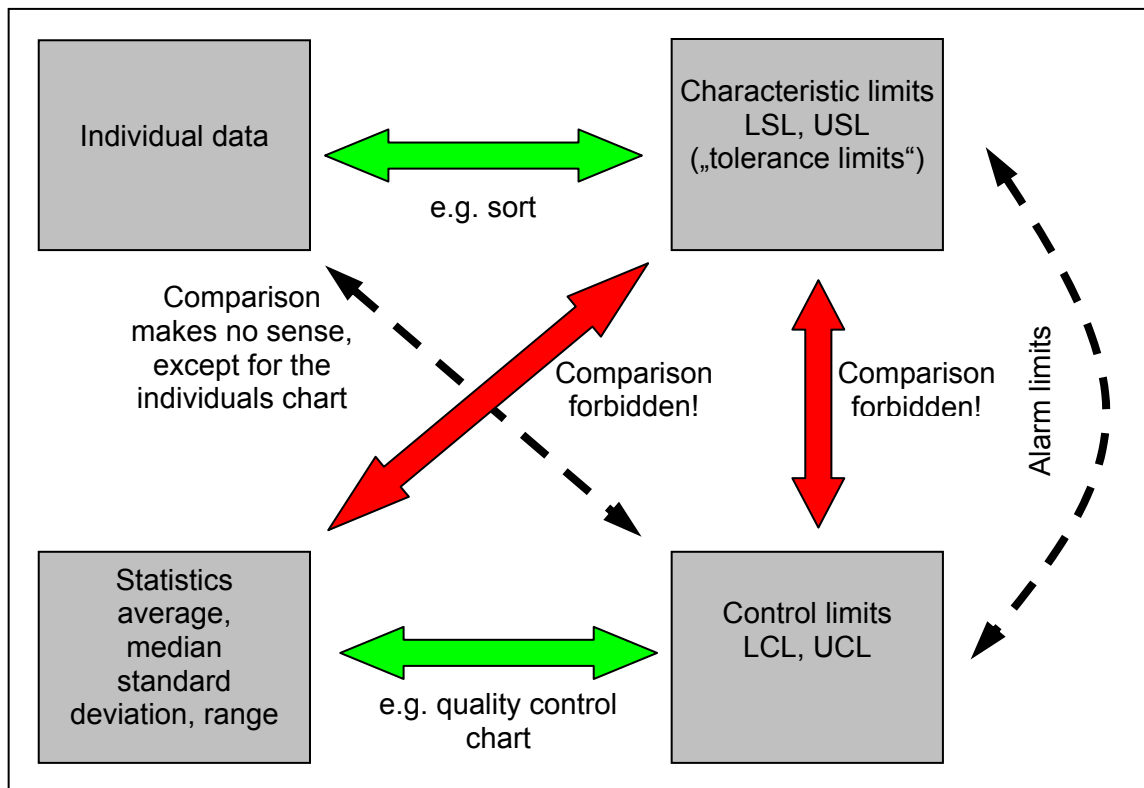
Use of the rule of 7 in this case (the same as comparing a random sample statistic with the control limits) is a statistical test with a probability of error (type I error) of  $\approx 1 \%$ .

For the given assumptions, the probability that at least 7 points in a row form a continuously increasing or decreasing trend is also very low.





## 5.5 Which Comparisons Can be Made?



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As the figure in Section 4.1 shows, the distribution of averages  $\bar{x}$  is significantly “narrower” than the distribution of the individual data. If a random value average is outside of the control limits but still inside of the “tolerance limits”, then possibly individual measurements were outside of the tolerance range. This is why it is not allowed to compare statistical values with characteristic specifications LSL/USL (“tolerance limits”).

For the same reason, it is not allowed to compare the difference  $UCL - LCL$  with the tolerance  $USL - LSL$ . The distance between the process-related control limits is dependent on the amount of process variation and may not be interpreted as a “reduced tolerance”.

Comparison of process-related control limits LCL/UCL with tolerance-related control limits (alarm limits) per Section 4.3 allows us to assess the amount of variation and the quality capability of a process.



## 6. Quality Control, Documentation

### 6.1 Evaluation

Define who will evaluate the data (completed control charts or after a defined time period). The following statistics can be calculated and documented:

$\bar{\bar{x}}$  (or  $\bar{\tilde{x}}$ ) per Section 3.4  
 $\bar{s}$  (or  $\bar{R}$ ) per Section 3.5  
 $\hat{\sigma}$  per Section 3.5

$C_p$  and  $C_{pk}$  or refer to [11]

$P_p$  and  $P_{pk}$  refer to [11]

taking applicable requirements (e.g. from customers) into account.

Check whether the process parameters and process capability indices  $C_p$  and  $C_{pk}$  or process performance indices  $P_p$  and  $P_{pk}$  have changed from the trial run or from previous charts.

Procedures for calculating these indices are described in [11].

New control limits are only calculated after process changes have been proven effective, e.g.:

- Technical improvements
- Reduction or elimination of previously observed changes of averages
- Reduction of internal process variation

Otherwise, the control limits remain constant.

It is recommended to periodically evaluate  $C_{pk}$  or  $P_{pk}$  on an overall basis.

### 6.2 Documentation

Define when the evaluation results and/or overall summaries are to be submitted.

Archiving duration is defined in QSP0206 [2] and in business division procedures.

Define the type and location for archiving.



## 7. SPC with Discrete Characteristics

### 7.1 General

In the past, np, p, c and u charts were used to control discrete characteristics. The way these charts work presumes a relatively high percentage of defects, which is unacceptable considering currently achieved ppm levels and our zero defect target.

For this reason, random sample testing of discrete characteristics no longer makes sense.

If necessary, refer to [7] for information on these control charts.

### 7.2 Defect Tally chart for 100% testing

The number or fraction of defects found during, for example, (end of line) visual inspection after a sequence of process steps (e.g. assembly) is often tracked together with 100% testing.

A defect tally chart can be used for this purpose.

In 100% testing, usually the production quantity from one shift is the reference quantity, and the defects (several types of defects) found for this shift are registered.

This type of registration of defects is not a random sample test in a statistical sense.

Nevertheless, a graph can be used to visualize the quality level from the beginning to the end of the shift with the fraction of individual and total defects  $p$  per shift.

Of course we need to check after each entry, also for 100% testing, whether intervention is necessary and to implement actions according to the applicable reaction plan (as in Section 5.4), if applicable.

Evaluation (e.g. with a Pareto analysis) and archiving as in Section 6.

The following procedure has worked well for calculating control limits for the fraction of defects:

- Calculate the average fraction of defects  $\bar{p}$  and the standard deviation  $s_p$  of the fraction of defects  $p$  (in % or ppm)
- Calculate the control limits (simple approximation):

$$UCL = \bar{p} + 2 \cdot s_p$$

$$LCL = \bar{p} - 2 \cdot s_p$$

Monitoring the overall fraction of defects as the sum of defect fractions for various types of defects only provides an overview for tracking defects, with the same weighting for each type of defect and without recognizing shifts among the types of defects that are registered.

This disadvantage can be eliminated by entering the fraction of each individual type of defect in the defect tally chart and by calculating the control limits for each individual type of defect, as described above.

The control limits can be calculated exactly using the Poisson distribution.



## 8. Tables ( $P_A = 99\%$ )

**Table 1**

Constants to estimate the standard deviation (Section 3.5)

$n$	$a_n$	$d_n$
2	0.798	1.128
3	0.886	1.693
4	0.921	2.059
5	0.940	2.326
6	0.952	2.534
7	0.959	2.704
8	0.965	2.847
9	0.969	2.970
10	0.973	3.078

**Table 2a**

Constants to determine the control limits of the individual data chart (Section 4.2)

$n$	$E'_E$
2	2.807
3	2.934
4	3.023
5	3.089
6	3.143
7	3.188
8	3.226
9	3.260
10	3.289

$$\hat{\sigma} = \frac{\bar{s}}{a_n}; \quad \hat{\sigma} = \frac{\bar{R}}{d_n}$$

$$E'_E = u_{n\sqrt{1-\alpha}} \quad \alpha = 1\% \quad (\text{two-sided})$$

**Table 2b**

Constants to determine the control limits (Section 4)

$n$	Process Location			Process Variation					
	$\tilde{x} - R$	$\bar{x} - s$	$x - R$	$s$ chart				$R$ chart	
	$C_E$	$A^*$	$E_E$	$B'_{Eun}$	$B'_{Eob}$	$B^*_{Eun}$	$B^*_{Eob}$	$D_{Eun}$	$D_{Eob}$
2	1.614	2.283	2.487	0.006	2.807	0.008	3.518	0.008	3.518
3	1.019	1.678	1.734	0.071	2.302	0.080	2.597	0.080	2.614
4	0.683	1.398	1.468	0.155	2.069	0.168	2.245	0.166	2.280
5	0.593	1.225	1.328	0.227	1.927	0.242	2.050	0.239	2.100
6	0.471	1.105	1.240	0.287	1.830	0.302	1.924	0.296	1.986
7	0.437	1.015	1.179	0.336	1.758	0.350	1.883	0.341	1.906
8	0.371	0.944	1.133	0.376	1.702	0.390	1.764	0.378	1.846
9	0.354	0.886	1.098	0.410	1.657	0.423	1.709	0.408	1.798
10	0.311	0.837	1.069	0.439	1.619	0.451	1.664	0.434	1.760
	$\tilde{x}: UCL = C + C_E \cdot \bar{R}$ $\tilde{x}: LCL = C - C_E \cdot \bar{R}$			$UCL = B'_{Eob} \cdot \hat{\sigma}$ $LCL = B'_{Eun} \cdot \hat{\sigma}$				$UCL = D_{Eob} \cdot \bar{R}$ $LCL = D_{Eun} \cdot \bar{R}$	
	$\bar{x}: UCL = C + A^* \cdot \bar{s}$ $\bar{x}: LCL = C - A^* \cdot \bar{s}$			$UCL = B^*_{Eob} \cdot \bar{s}$ $LCL = B^*_{Eun} \cdot \bar{s}$					
	$x: UCL = C + E_E \cdot \bar{R}$ $x: LCL = C - E_E \cdot \bar{R}$								



## 9. Example of an Event Code for Mechanically Processed Parts

It is necessary to make a distinction between the event code that the machine operator needs and the event code for his foreman. The event codes for the foreman may not be used by the machine operator, nor may he make the decisions.

The following plan for the operator level is divided up into causes, action and handling of parts/goods.

### 9.1 Causes

C1	Batch change in the materials	S2	Work piece clamping device, breakage
C2	Batch change in processing	S3	Work piece limit stop defective
		S4	Work piece drive unit defective
K1	Calibration not correct	V1	Incoming goods are dirty
K2	Reference standard defective	V2	Inspection instrument is dirty
M1	Machine defect, mechanical	V3	Machine is dirty
M2	Machine defect, electrical	V4	Preparation/condition nonconforming
M3	Machine defect, hydraulic		
M4	Machine failure in the conveyor system	W0	Tool defective
		W1	Tool, end of tool life
P1	Individual value not plausible	W2	Tool, breakage
P2	Measuring/inspection equipment defective	W3	Tool holder defective
		W4	Tool dressing device defective
S1	Work piece clamping device, tool life	Z1	Determine other causes

### 9.2 Action

A1	Termination of the inspection during a sample, since the values up to now have all been outside the plausibility area.	M6	Machine cleaned
		M7	Machine serviced/repaired
A2	Termination of the inspection after completing a sample, since it is beyond the control limits and it is expected that it will affect subsequent characteristics.	P3	Inspection equipment changed
		P4	Inspection controller changed
		P5	Inspection equipment adjusted
		P6	Inspection equipment cleaned
		P7	Inspection repeated
A3	Termination of the inspection so that it can be resumed later.	S5	Tool holder changed
		S6	Work piece limit stop corrected
		S7	Work piece drive unit corrected
K3	Calibration repeated		
K4	Calibration repeated with new standard	W5	Tool adjusted
K5	Calibration carried out	W6	Tool changed
		W7	Tool holding device corrected
M5	Machine adjusted	W8	Tool dressed
		W9	Tool dressing device corrected



**9.3 Handling of the Parts/Goods**

- |    |  |    |   |
|----|--|----|---|
| T1 | Control limits exceeded; a recheck did not reveal any necessity for sorting; parts/goods delivered as OK | T5 | Parts/goods to be scrapped 1)   |
| T2 | 100% sorted, OK portion was delivered  | T6 | 100% sorted, concession portion delivered 1)                            |
| T3 | Parts/goods delivered with concession 1)   | T7 | 100% sorted, OK or concession portion delivered, rework portion kept 1) |
| T4 | Parts/goods blocked; rework required   | Z3 | Determine other form of handling  |

1) As a rule, the machine operator does not make the decisions on these matters.

**9.4 Action Catalog**

**An action catalog needs to be created especially for the specific process being controlled (machine, test location).**

The event codes listed in the previous sections are only meant to be examples, which in this case refer to a mechanical manufacturing process.

An example is shown on the next page, including sorting instructions.



## Example: Action Catalog for SPC

Measuring position no.: 82

If the control chart reacts the following actions must be taken and entered in the chart:

After action on the process take a sample and enter measured values in the control chart!

### Action Plan:

**Goods:**

- 11. 100% sorting, OK-proportion delivered
- 12. Goods delivered with concession
- 13. Goods held; rework necessary
- 14. Scrap

**Tool:**

- 21. Dress grinding wheel
- 22. Change grinding wheel

**Work piece:**

- 31. Change chuck
- 32. Stop dog

**Machine:**

- 41. Adjust machine
- 42. Machine defect mech./hydr./pneum.
- 43. Machine defect electrical
- 44. Change dressing tile
- 45. Change dressing rollers

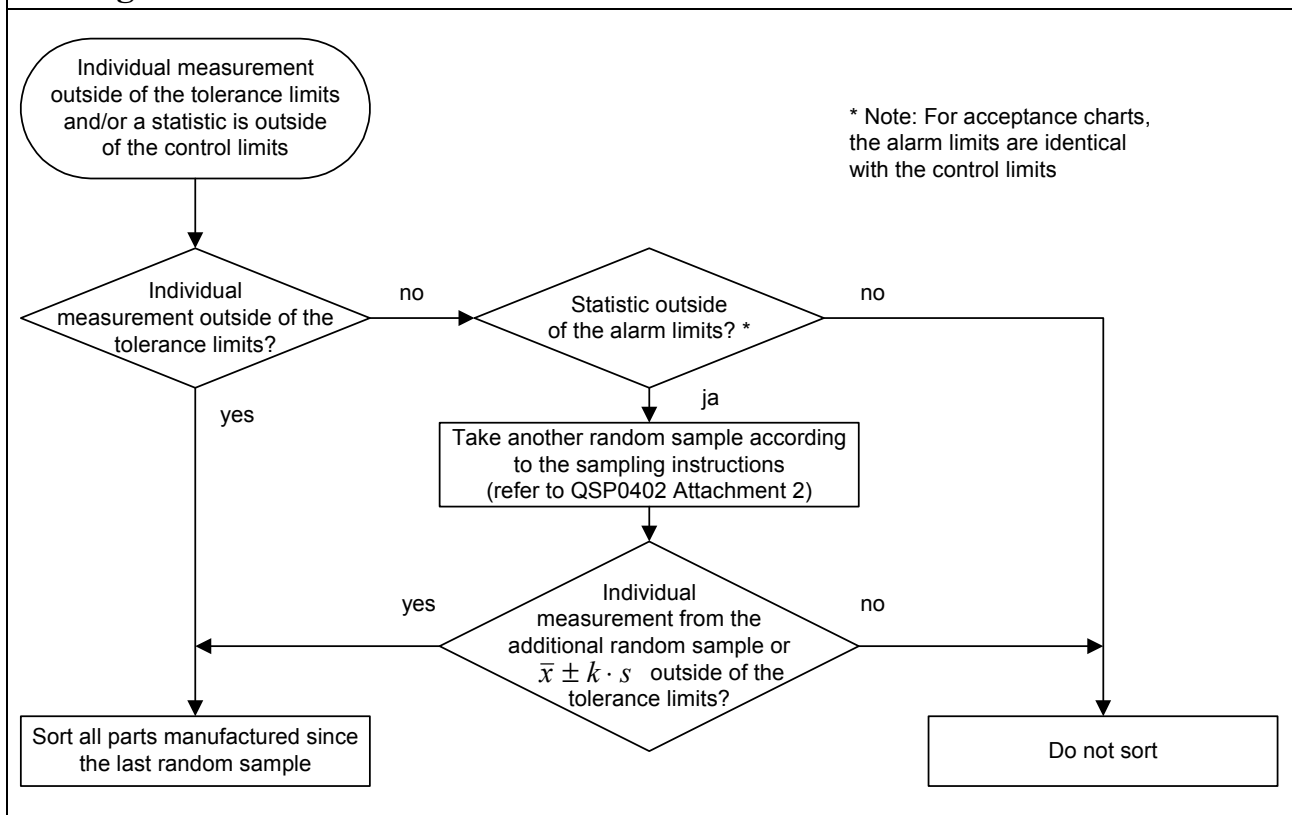
**Measurement system:**

- 51. Change of gage caliper
- 52. Measurement control/compensation

**General:**

- 61. Contamination
- 62. Preliminary working/delivery
- 63. Other causes (to be documented)

### Sorting Instruction:




Workshop: 580  
Equipment: Junker 640 571

Product/Part: Cam plate  
Working operation: Grind driver, WO 1151  
Date: 17.01.2004



10. Example of an  $\bar{x} - s$  Chart

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 <b>BOSCH</b> Quality Management		Quality Control Chart for Continuous Characteristics																				Part		Department	
		Characteristics																				Flange 1 ... 027		W410	
		Diameter																				1130, precision-turn		Control chart by $\Delta m_{lib}$	
X <sub>1</sub>	63	63	63	61	62	61	62	63	64	63	62	60	62	60	62	62	60	62	62	61	59	Machine	...	Spindle	
X <sub>2</sub>	63	63	63	60	62	62	61	62	64	63	64	61	65	62	63	61	63	61	63	63	64	Machine no.	...	....	
X <sub>3</sub>	62	62	61	59	63	63	62	63	63	61	64	63	64	65	63	62	62	63	65	64	64	USL	48,69		
X <sub>4</sub>	63	63	63	63	63	61	62	63	60	65	62	63	65	61	64	59	61	63	65	60	62	Center point C	48,62		
X <sub>5</sub>	62	63	62	62	60	62	61	63	63	62	63	62	63	62	60	62	63	63	62	64	65	LSL	48,55		
$\bar{x}$	62,6	62,8	62,4	61,0	62,4	61,8	61,6	62,2	63,4	62,0	63,4	61,8	63,2	63,0	61,4	62,4	60,4	61,6	62,8	62,2	61,6	Reference value	48,00		
S	0,55	0,45	0,89	1,58	0,55	1,30	0,55	0,84	0,55	1,41	1,34	1,30	1,30	2,12	2,07	1,14	1,14	0,55	0,45	2,28	1,48	Unit	0,01 mm		
																						Sample size	5		
																						Frequency	every 150 parts		
																						Additional test	EII		
																						Control limits for	<input checked="" type="checkbox"/> $\bar{x}$	<input type="checkbox"/> $\sigma$	
																						Process related	<input checked="" type="checkbox"/>		
																						Tolerance related	<input type="checkbox"/>		
																						UAL	64,6		
																						UCL	63,6		
																						Target value	62,0		
																						LCL	60,4		
																						LAL	59,4		
																						Control limits for	<input checked="" type="checkbox"/> s	<input type="checkbox"/> R	
																						UCL	2,6000		
																						Central line	1,300		
																						LCL	0,3000		
																						Evaluation			
																						$\bar{x}$	62,3		
																						$\bar{s}$	1,27		
																						$\hat{\sigma}$	1,35		
																						Cp	1,73		
																						Cpk	1,66		
Date	11.10.	11.10.	11.10.	11.10.	12.10.	12.10.	12.10.	13.10.	13.10.	13.10.	14.10.	14.10.	14.10.	14.10.	15.10.	15.10.	15.10.	15.10.	16.10.	16.10.	18.10.	Corrective action (see overleaf)			
Time	6:50	11:40	14:40	20:35	6:25	10:50	14:20	21:05	6:20	10:15	15:00	21:35	7:10	11:50	16:05	21:30	6:50	12:10	16:15	21:20	6:45	Evaluated	18.10.	19.10.	
Name	$\Delta m$	$\Delta m$	$\Delta m$	$\Delta m$	$\Delta m$	$\Delta m$	$\Delta m$	$\Delta m$	$\Delta m$	$\Delta m$	$\Delta m$	$\Delta m$	$\Delta m$	$\Delta m$	$\Delta m$	$\Delta m$	$\Delta m$	$\Delta m$	$\Delta m$	$\Delta m$	$\Delta m$	Checked	21:15	6:50	





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## 12. Symbols

		Section(s)
$\mu$	= Mean of the population .....	Introduction
$\hat{\mu}$	= Estimation of the mean .....	3.4
$\bar{x}$	= Arithmetical mean based on $n$ measured values .....	1
$\tilde{x}$	= Median .....	1
$\overline{\bar{x}}$	= Arithmetical mean based on $m$ samples each of $n$ units .....	3.4
$\overline{\tilde{x}}$	= Arithmetical mean of $m$ medians .....	3.4
$\sigma$	= Standard deviation of the population.....	Introduction
$\hat{\sigma}$	= Estimation of the standard deviation of the population .....	3.5
$s$	= Standard deviation of a sample .....	1
$\bar{s}$	= Arithmetical mean of standard deviations .....	3.5
$s_{\bar{x}}$	= Standard deviation of mean values .....	4.1.2
$s_p$	= Standard deviation of the nonconforming fraction $p$ .....	7.2
$s_{total}$	= Standard deviation of all individual values .....	4.1.2
$R$	= Range of a sample .....	1
$\bar{R}$	= Arithmetical mean of ranges .....	3.5
$\hat{\mu}_{max}$	= Estimation of the largest mean value .....	4.1.2
$\hat{\mu}_{min}$	= Estimation of the smallest mean value .....	4.1.2
$C_p, C_{pk}$	= Process capability index .....	6.1
$P_p, P_{pk}$	= Process performance index .....	6.1
$UAL$	= Upper alarm limit .....	4.3
$USL$	= Upper specification limit .....	1
$LSL$	= Lower specification limit .....	1
$T$	= Tolerance; $T = USL - LSL$ .....	1
$UCL$	= Upper control limit .....	4.1
$LAL$	= Lower alarm limit.....	4.3
$LCL$	= Lower control limit .....	4.1
$C$	= Target value (center point of the tolerance zone) .....	1
$k_A$	= Delimitation factor in the $\bar{x} - s$ chart .....	4.2
$k_E$	= Delimitation factor in the individual data chart .....	4.2
$np$	= Number of nonconforming units .....	7.1
$p$	= Proportion of nonconforming units .....	7.1, 7.2
$\bar{p}$	= Average proportion nonconforming .....	7.1, 7.2
$c$	= Number of nonconformities per product unit .....	7.1
$u$	= Average number of nonconformities per product unit .....	7.1
$n$	= Size of an individual sample .....	1
$m$	= Number of individual samples .....	3.4, 3.5
$N$	= Total number of all individual values ( $N = m \cdot n$ ) .....	4.1.2
Constants: $a_n, c_n, d_n, A, A', A^*, B'_{Eun}, B'_{Eob}, B^*_{Eun}, B^*_{Eob}, C_E, D_{Eun}, D_{Eob}, D'_{ob}, E_E, E'_E$		



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